Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/7130--12-9408

NRL Technical Year End Progress Report for MCSC PM-ICE FY11 SOW Tasks 1 and 2 — Hearing Loss Research

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May 18, 2012

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
18-05-2012

2. REPORT TYPE
Memorandum Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

NRL Technical Year End Progress Report for MCSC PM-ICE
FY11 SOW Tasks 1 and 2 — Hearing Loss Research

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory, Code 7130
4555 Overlook Avenue, SW
Washington, DC 20375-5350

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7130--12-9408

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Program Manager, Infantry Combat Equipment (PM ICE)
Marine Corps Systems Command
Quantico, VA 22134

10. SPONSOR / MONITOR'S ACRONYM(S)

PM ICE

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A human surrogate was recently developed to emulate the acoustic transmission path of a human ear. This physical model was used to study soldier exposure to impulsive small weapons fire. The ear response of the surrogate and human data are in very good agreement. The effect of the helmet and body armor equipment on a soldier's hearing was determined in this report through laboratory and firing range measurements. A sound pressure level (SPL) reduction of 2 to 3 dB on both left and right inner ears of the surrogate was found when a helmet was worn. This reduction was probably due to the helmet blocking the direct acoustic path from the weapon muzzle to the ear. Body armor appears to have very little effect on the sound reaching the inner ears. This implies that reflections from the torso are a second order effect when compared to the direct acoustic path. The physics of the direct acoustic path from the weapon muzzle to the ears appears to be the most important acoustic mechanism affecting the inner ear SPL levels. The surrogate developed here may serve as a "standard" for human hearing evaluation of infantry combat equipment and weapons systems deemed relevant to the warfighter.

15. SUBJECT TERMS

Hearing loss   Small weapons fire
Human ear   Shooter's notch

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unclassified Unlimited	27	Peter C. Herdic
					19b. TELEPHONE NUMBER *(include area code)* (202) 404-8265

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

CONTENTS

NRL Technical Year End Progress Report for MCSC PM-ICE
FY11 SOW Task 1 and 2 –Hearing Loss Research

1. PROGRAM OVERVIEW

A human surrogate was recently developed to emulate the acoustic transmission path of a human ear. This physical model was used to study exposure to impulsive small weapons fire. The construction of the surrogate was completed and validated against human data in FY10. The surrogate serves as a 'standard' for the human hearing evaluation of infantry combat equipment deemed relevant to the warfighter. In this study, the effect of the helmet and body armor equipment on a soldier's hearing is determined through laboratory and firing range measurements conducted in FY11.

2. SURROGATE

Both ears of the surrogate were modeled, including the soft circumaural area around the ears, pinna, concha and ear canal as shown in Fig. 1. At the end of each ear canal there is a high dynamic range pressure sensor (PCB P113A21) for measurement at the inner simulated ear drum surface. The surrogate head is filled with a lead mixture to reduce multipath effects and internal resonances. Bone conduction transmission paths were not modeled, but this mechanism will be discussed later in this report. The full body of the surrogate physical model was included to allow for secondary acoustic reflections from the torso. The ear inserts are a product of Head Acoustics, Brighton, MI, and the pressure sensors are made by PCB Piezotronic, Depew, NY.

Fig. 1 — Surrogate head with both ears modeled including circumaural area, pinna, concha, ear canal, and high dynamic range pressure sensors (not shown) at the end of each ear canal chamber.

Manuscript approved February 1, 2012.

3. TASK 1 – LABORATORY MEASUREMENTS

The experimental configuration is depicted in Fig 2. An acoustic loud-speaker insonifies the surrogate, and the pressure response of each ear is recorded over a band of 0.2 to 20 kHz. The surrogate is mounted on a rotating stage that allows for 360 degree aspect angle rotation relative to the source. For the physical model validation, the surrogate transfer function of the ear (TFOE) was compared to human data obtained from Shaw, E., Handbook of Sensory Physiology, Vol. V/1, pp 455-473, Springer, Berlin, Heidelberg. New York, 1974. These comparisons are shown in Fig. 3 for normal and grazing incidence. Agreement is very good with perhaps a slight shift upward in the fundamental ear canal resonance of the surrogate around 4 kHz. The resonance shift is consistent with size differences in the ear canal of the human subject and surrogate.

Fig. 2 — Laboratory experimental configuration. The surrogate is mounted on a rotator that allows for 360 degree aspect rotation relative to the acoustic source.

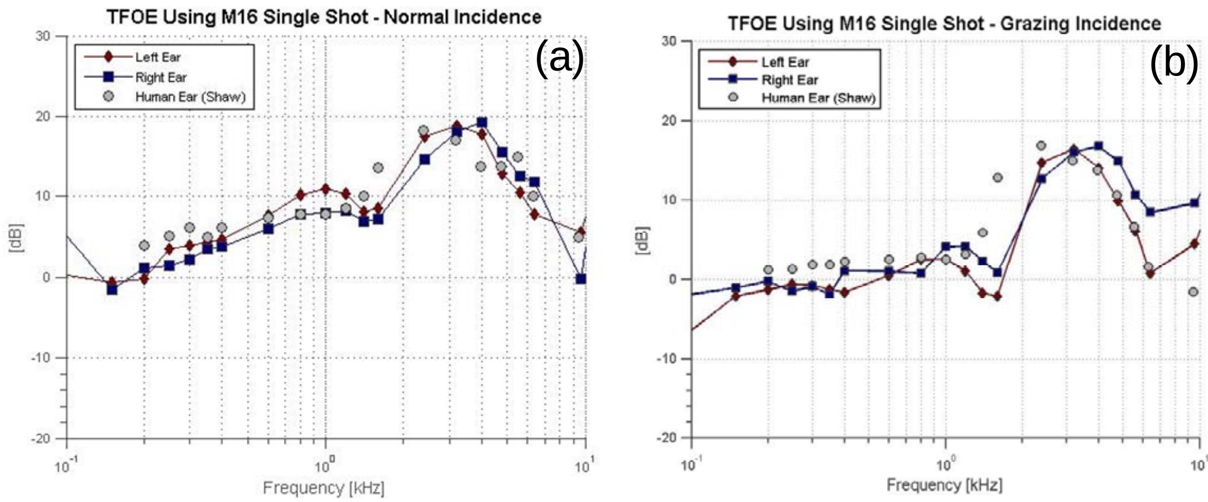


Fig. 3 — Comparison of surrogate left (red) and right (blue) transfer function of ear (TFOE) compared with human data (gray) from Shaw, et. al. for (a) normal incidence and (b) grazing incidence.

Full 360 degree TFOE (dB) displays of the left and right inner ear responses are shown in Fig 4 for four separate configurations of the surrogate: *without helmet or armor*, *helmet only*, *helmet and armor* and *armor only*. The reference to helmet refers to donning the surrogate with a Marine LWH, size large, with a standard configuration of Team Wendy Pads. The reference to armor refers to donning the surrogate with an MTV with 2 E-SAPI plates inserted. These displays are over a band of .2 to 20 kHz. In the frequency band above 15 kHz, the integrity of the signal is degraded somewhat by noise, but still yields useful information. The displays show a full 360 degree response with 0 degrees being when the surrogate's face is toward the loud speaker acoustic source (grazing incidence), and the left and right ears face the source at -90 and +90 degrees (normal incidence), respectively. Three ear canal resonances are clearly observed in the response. The fundamental resonance is fairly broad and centered around ~4 kHz. The first and second harmonics are at ~12.5 kHz and ~18 kHz. These frequencies are consistent with the resonances of a tube that is open on one end and closed on the other end such as an organ pipe with the same dimensions as the ear canal. The TFOE is referenced to the pressure level at the surrogate head center (surrogate removed for measurement). Therefore, levels above 0 dB indicates amplification of the exterior sound by the ear canal resonances. The left and right ear responses are not identical due to manufacturing imperfections, but this would also be the case with a human having some differences between each ear.

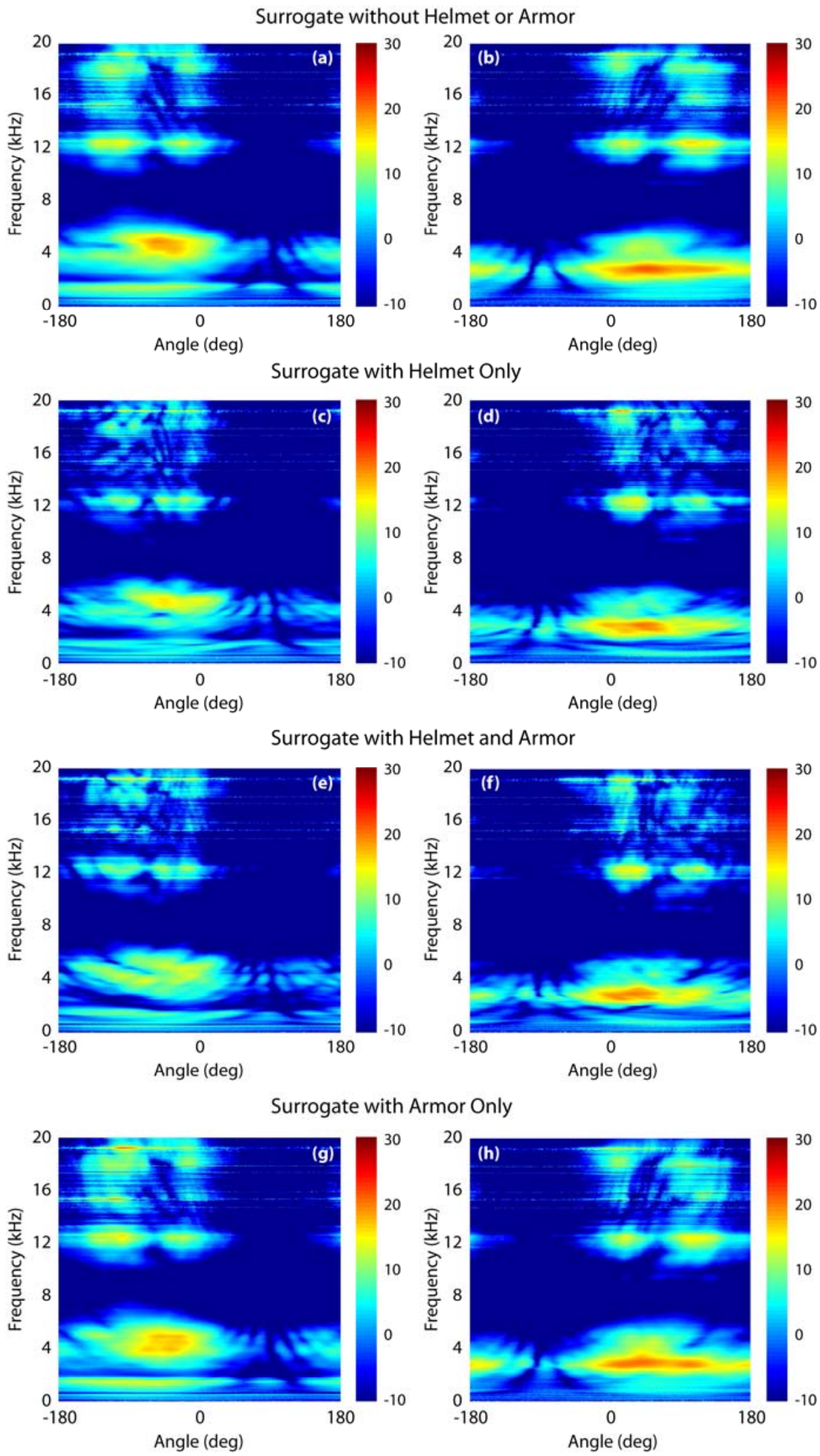


Fig. 4 — Full 360 degree laboratory TFOE (dB) display for (a) left and (b) right ear of *surrogate without helmet or armor*, (c) left and (d) right ear of *surrogate wearing helmet only*, (e) left and (f) right ear of *surrogate wearing helmet and armor*, and (g) left and (h) right ear of *surrogate wearing armor only*.

One clear observation from this data is that there is a slight sound pressure level (SPL) reduction when the helmet is worn by the surrogate. This is quantified in the root-mean-squared (RMS) TFOE curves in Fig. 5 that have been spatially averaged over the full 360 degrees of aspect angles. There is clearly a 2-3 dB reduction in the sound level in the helmet cases at the ear canal resonances. The helmet is acting as a barrier, blocking a portion of the sound reaching the ear. The armor appears to have little effect on the sound entering the ear. This indicates that reflections from the torso are likely a second order effect when compared to the direct acoustic path. Again note that there is some reduced signal-to-noise ratios above approximately 15 kHz.

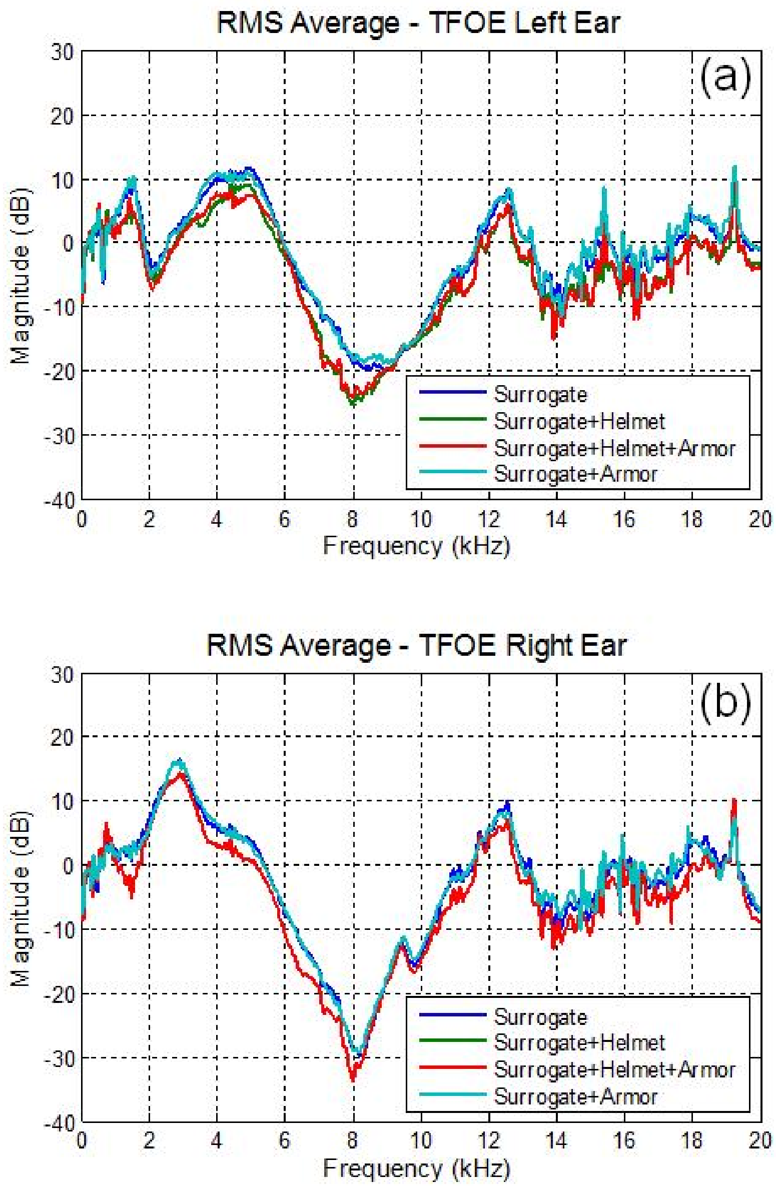


Fig. 5 — RMS aspect angle averaged TFOE for (a) left and (b) right ears determined in the laboratory. These curves show the effect of surrogate hearing in configurations *without helmet or armor* (dark blue), *with helmet only* (green), *with helmet plus armor* (red) and *with armor only* (light blue). Note the nominal 2-3 dB of noise reduction around ear canal resonances when wearing the helmet.

A SPL performance metric, expressed as a dB difference, was developed to compare the different configurations in the laboratory and at the firing range,

$$SPL \quad Performance\ (dB\ Difference) = 20 * \log_{10}\left(\frac{\sum_{f=2kHz}^{6kHz}\left|SP_{with\ Equipment}\right|}{\sum_{f=2kHz}^{6kHz}\left|SP_{without\ \ Equipment}\right|}\right) \tag{1}$$

where,

$$\left|SP\right| = \sqrt{\mathrm{Re}^2(SP) + \mathrm{Im}^2(SP)}$$

$$SP = Fast\,Fourier\,Transform(sp) = \sum_{k=0}^{N-1} sp_k e^{i2\pi k/N}$$

sp_k is the kth point of the sound pressure time history of N total points. The results of this metric yield a dB level difference of SPL between the surrogate wearing and not wearing the equipment of interest. Negative numbers indicate a SPL dB reduction due to the equipment being worn. Recall that the SPL is measured at the surrogate's inner ear, representing the ear drum surface. The sound pressure is summed over a frequency band from 2-6 kHz as this is around the first ear canal resonance centered at 4 kHz. It is also well known that there is a 'shooters notch' of hearing loss around 4 kHz in the hearing of infantry firing small weapons. The earliest reference to this hearing loss notch due to weapons firing is Toynbee, J. *Diseases of the Ear: Their Nature, Diagnosis, and Treatment,* London, Churchill, 1860. When applying this SPL performance metric to the laboratory RMS spatially averaged data, a 2.8 dB (left ear) and 2.0 dB (right ear) reduction was found for the surrogate wearing the *helmet only*, a 2.9 dB (left ear) and 2.3 dB (right ear) reduction was found for the surrogate wearing *helmet and armor*, and a 0.1 dB reduction was found in each ear for surrogate wearing *armor only.* The armor has a negligible effect on the sound reaching the inner ear.

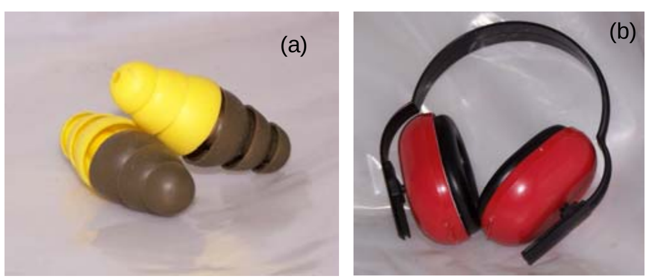


Fig. 6 — Devices used as samples for hearing protection evaluation: (a) combat ear plugs and (b) ear muffs.

Additionally, two types of hearing protection devices were evaluated with the surrogate. Photos of the devices are shown in Fig. 6. The combat ear plug device was obtained at Aberdeen Proving Ground during our visits there in preparation for the firing range portion of our measurements. The other device is an ear muff that is routinely worn in our laboratory for ear protection. Fig. 7 shows the full 360 degree TFOE of the left and right ears for the surrogate *without hearing protection*, *with combat ear plug protection* and *with ear muff protection.* Note the significant reduction in the cases with ear protection and that the color bar for these displays is reduced by 20 dB when compared to the display without ear protection. The performance curves in Fig. 8 further indicate this strong reduction. The dB reduction curves (red) shows 20-30 dB of attenuation of sound due to each hearing protection device at the ear canal resonances for normal incidence. The narrow lines spanning the full set of aspect angles especially at higher frequencies are residual signal processing effects due to singularities created from the nulls in the reference signal and lower signal-to-noise ratios of the attenuated signal.

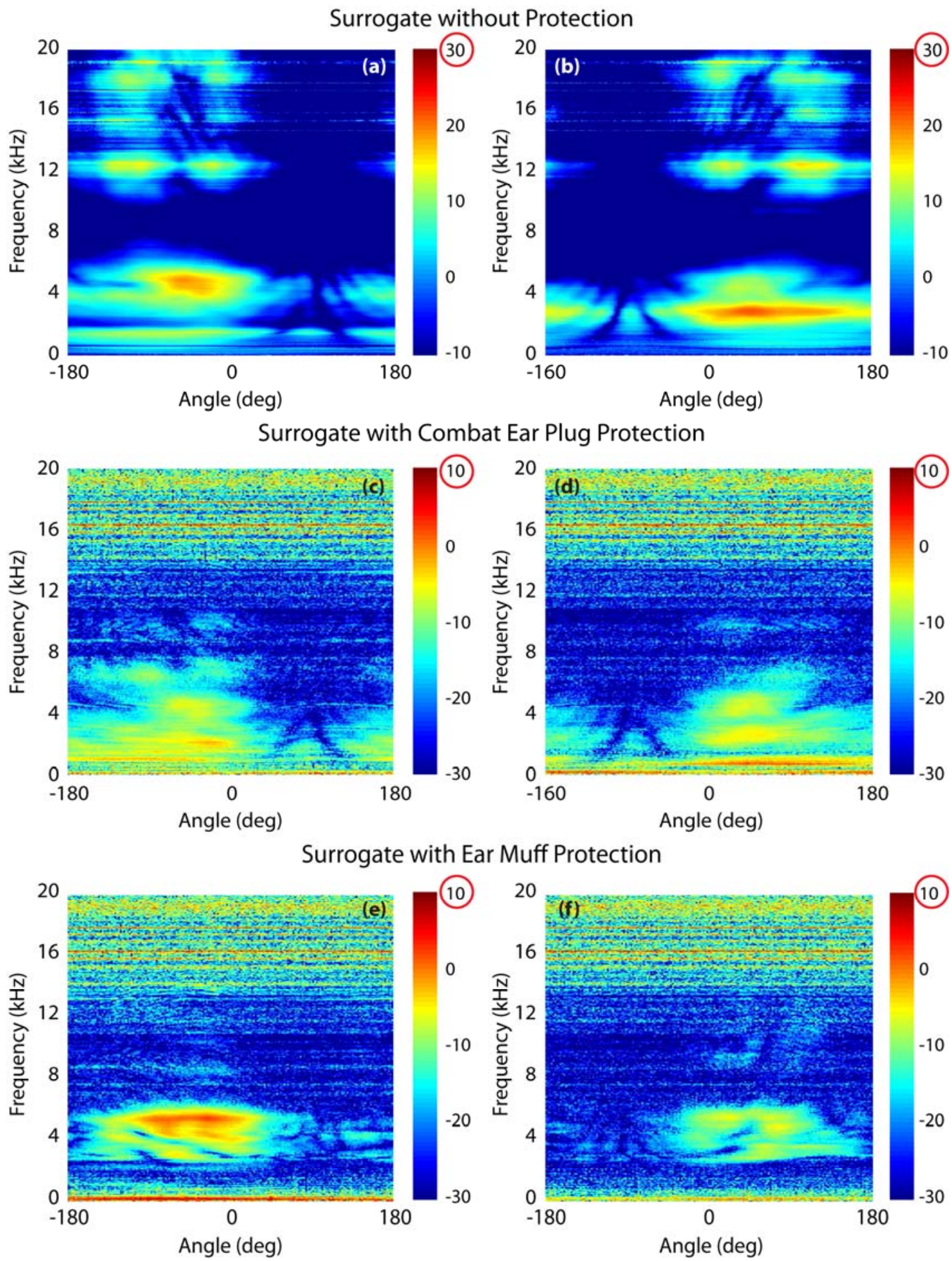


Fig. 7 — Full 360 degree laboratory TFOE (dB) display for (a) left and (b) right ear of surrogate *without ear protection*, (c) left and (d) right ear *with combat earplug protection,* and (e) left and (f) right ear *with ear muff protection.* Note that the color scale is 20 dB lower for the cases with hearing protection.

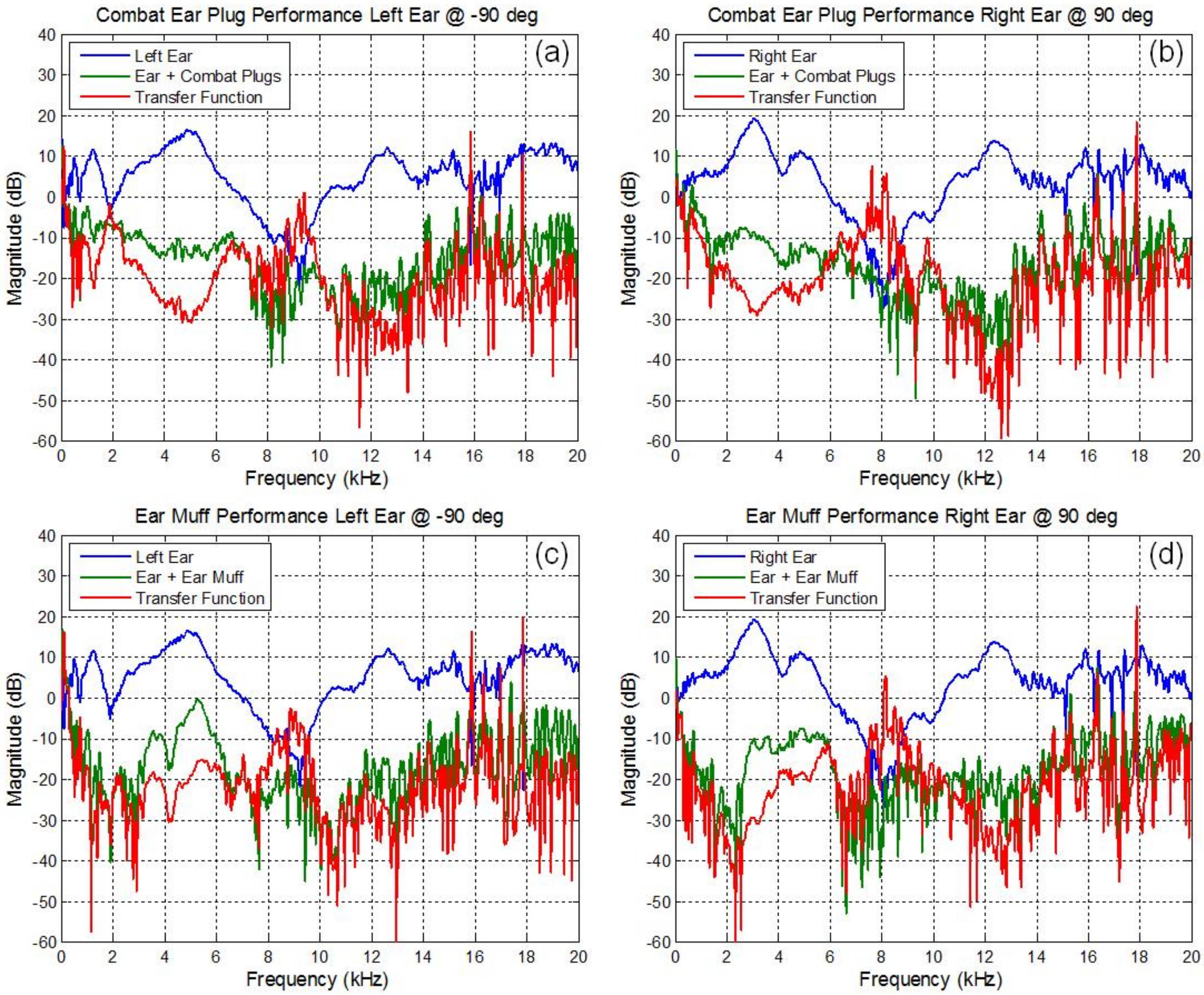


Fig. 8 — Performance curves for (a) left and (b) right ear using the combat ear plug protection, and (c) left and (d) right ear using the ear muff protection. The db reduction curve (red) is a transfer function of the ear plug protected ear (green) normalized by unprotected ear (blue) at normal incidence, showing 20-30 dB attenuation at ear canal resonances due to the hearing protection.

4. TASK 2 – FIRING RANGE MEASUREMENTS

Firing range measurements were made with the human surrogate at the Aberdeen Proving Ground, M-Range with the assistance of Mr. James Faughn from the Army Research Laboratory, Human Research and Engineering Directorate. The surrogate response of each ear to M16 rifle, M4 rifle, M240B machine gun, M249 SAW and M82 Barrett sniper rifle fire was recorded in a wood and composite foxhole. The M16, M4, and M249 used 5.56 ammunition, M240B used 7.62 ammunition and the M82 used .50 caliber. Data were recorded with a field system that simultaneously recorded three channels with a bandwidth ranging from 0.1 to 16 kHz. A photo of the surrogate positioned in the foxhole with the M240B is shown in Fig. 9. Mr. Faughn fired the weapon as shown in photo with the surrogate in the right handed firing position. A tripod was attached to surrogate, as shown Fig. 10, for the foxhole measurements. This allowed the surrogate head to be positioned with six degrees of freedom and placed in a realistic shooting stance. An acoustic reference was measured at the surrogate head center as shown in Fig. 11. These reference measurements represent the pressure level at the surrogate head center without the surrogate being present which are used to normalize the surrogate ear response to determine the TFOE at the firing range.

Fig. 9 — Human surrogate with helmet and armor positioned during foxhole firing measurements.

Fig. 10 — Tripod support for surrogate from the backside of foxhole

Fig. 11 — Acoustic reference configuration in foxhole. The two microphone positions represent head center references for the left and right handed shooter.

Five shots were recorded for each of the above weapons in three surrogate configurations: *without helmet or armor*, *wearing helmet only* and *wearing helmet and armor*. The time domain left ear response of the surrogate without helmet or armor for the five shots from the M16 rifle is shown in Fig 12. Note that the responses are fairly repeatable, but there is more variability than in the laboratory measurements. This variability is likely due to high phase sensitivity between acoustic direct and reflections as the result of environmental changes as well as due to shot to shot variability, or some combination thereof. Analysis involved careful placement of a time domain window on the response so as to minimize acoustic reflection interference. Some remnants of destructive interference can be seen in the form of sharp nulls in the frequency domain response of the same data shown in Fig. 13. Taking an amplitude average of these frequency domain responses (black curve) alleviates this variability to some degree while providing a representative measure of the response. The amplitude averages of the TFOE responses for the different configurations are shown in Fig. 14 for both the left and right ears using the M16 weapon in the foxhole. These displays are over a band from .2 to 16 kHz. The amplitude average curves for all the weapons in the foxhole can be found in the first four displays, Figs. A1-A4, Appendix I.

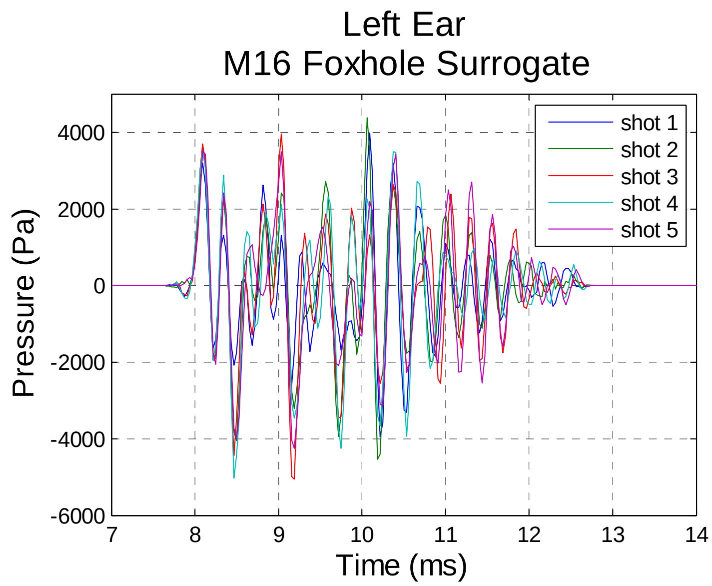


Fig. 12 — Display of time domain left ear response of surrogate without helmet and body armor for five shots of the M16 weapon in the foxhole.

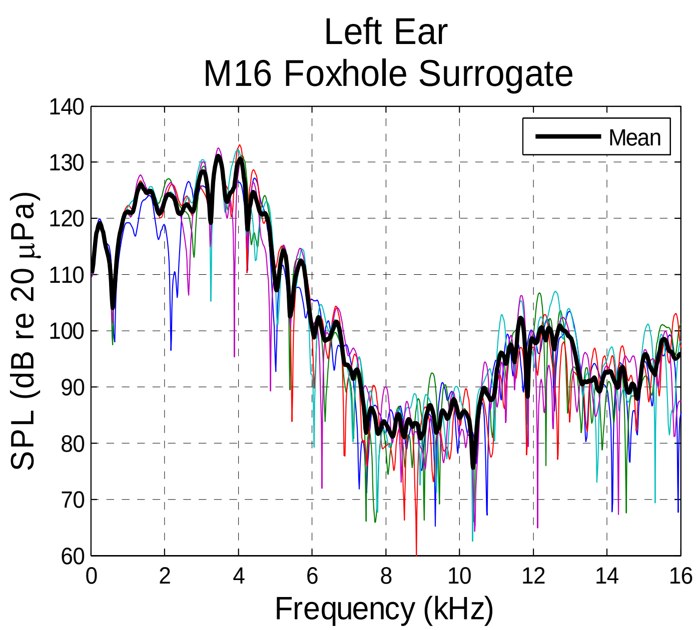


Fig. 13 — Display of frequency domain left ear response of surrogate without helmet and body armor from five shots of the M16 weapon in the foxhole and the amplitude averaged (black) curve.

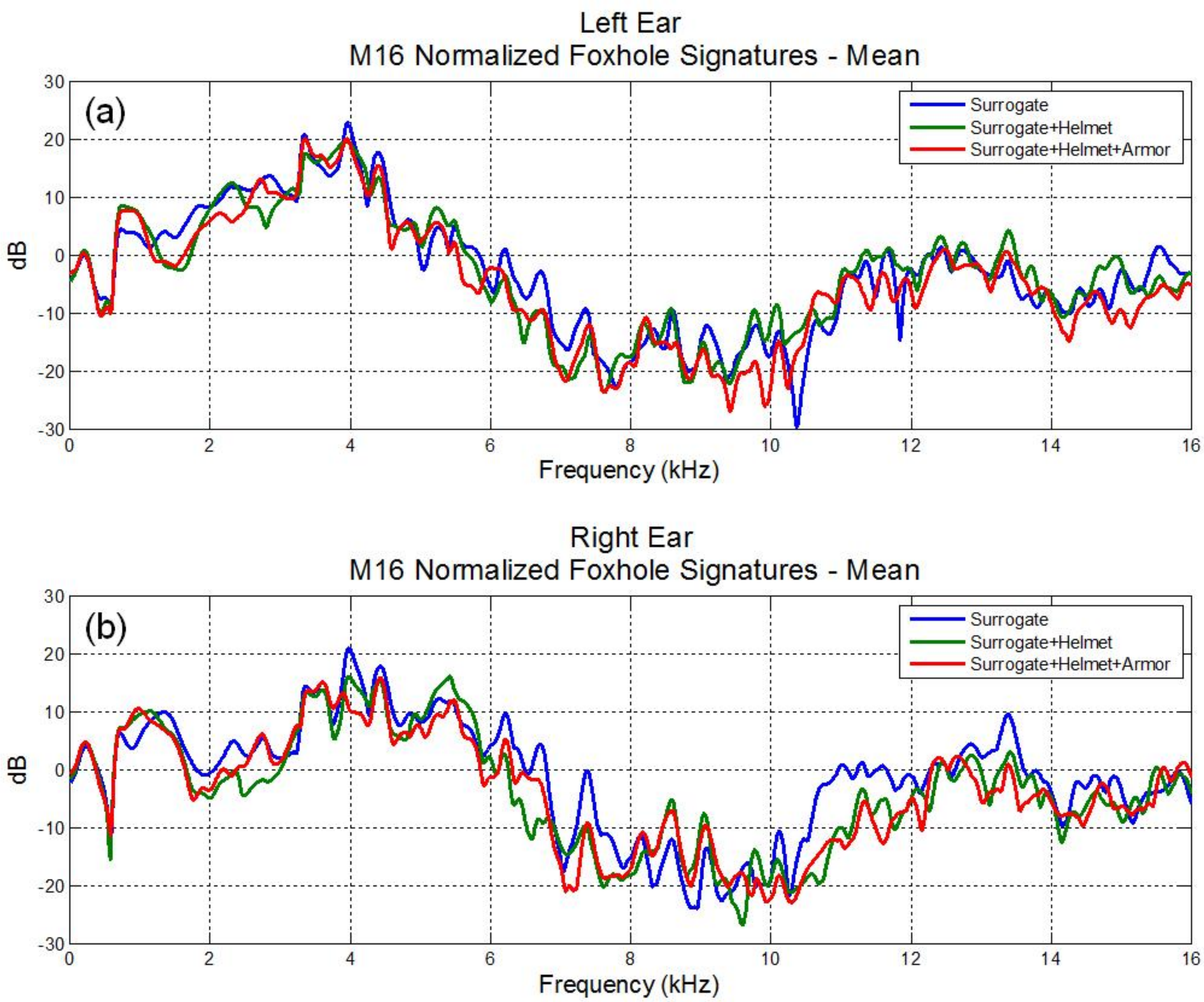


Fig. 14 — Display of frequency domain amplitude averaged TFOE response of (a) left ear and (b) right ear for the configuration of the surrogate *without helmet or armor* (blue), *wearing helmet* (green), and *wearing helmet and armor* (red) using the M16 weapon in the foxhole.

The firing range measurements were evaluated using the SPL performance metric in Eq. 1, and the results are shown in Table I for the foxhole configuration. The M82 weapon was left out of this analysis since the sniper shooter does not usually wear a helmet or armor. Recall, the SPL metric is the dB difference of SPL between the surrogate wearing and not wearing the equipment of interest. Negative numbers indicate a SPL dB reduction due to the equipment being worn. There is a 2.0 dB average reduction in SPL when the *helmet only* is worn and a 1.8 dB average reduction in SPL when the *helmet and armor* is worn. These results are in agreement with those obtained in the laboratory. Recall the laboratory results showed a 2-3 dB reduction in configurations whenever the helmet was worn. The firing range results have higher data variability as previously described. The laboratory measurements also showed that there was essentially no effect in the SPL when wearing armor. The average enhancement when the armor is worn in the field is .4 dB which is within the data variability or measurement error. The conclusion from both the laboratory and firing range measurements is that there is nominally a 2-3 dB reduction in the SPL in cases when the helmet is worn (helmet only or helmet plus armor) which is probably due to the direct acoustic path being somewhat blocked by the helmet equipment, and the armor has little to no effect on the SPL levels reaching the inner ear.

Table 1 — Foxhole SPL Performance Metric in 2-6 kHz Band (dB Reduction)

Weapon Configuration	Surrogate *left ear* + Helmet (dB)	Surrogate *right ear* + Helmet (dB)	Surrogate *left ear* + Helmet +Armor (dB)	Surrogate *right ear* + Helmet +Armor (dB)
M16 (foxhole)	-0.9	-1.3	-1.2	-2.4
M4 (foxhole)	-3.1	-2.8	-0.1	-1.6
M240B (foxhole)	-3.6	-2.6	-3.2	-3.1
M249B (foxhole)	-2.4	-0.2	-2.2	-0.8

Measurements were also made for the surrogate in a standing position using the M16 and M4 weapons. The photo in Fig. 15 shows this configuration of the surrogate, weapon and shooting method. The surrogate's legs have replaced the tripod, and the firing position is in a less natural firing stance with the surrogate head facing straight forward. The sound originating from the muzzle is hitting approximately normal to the face (0 degree incidence aspect angle in the laboratory measurements). The amplitude average curves for the standing position can be found in the last two displays, Fig. A5 and A6, Appendix I, and the dB difference metric results are in Table 2. Unfortunately, because the surrogate was not flexible enough to position in a realistic standing shooting stance, the results are somewhat different from the foxhole based measurements. The standing results showed a dB difference varying from +0.6 to -0.8 dB using the SPL performance metric in Eq. 1. These results are in agreement with the laboratory results that show a smaller effect of the equipment at the 0 degree grazing incidence angle (surrogate facing forward toward source). This conclusion can be drawn by examining the 0 degree laboratory responses in Fig 4. The effect of the direct acoustic path being block by the helmet is minimal in this 0 degree aspect configuration as the sound from the muzzle can pass relatively unabated to the ear.

Fig. 15: Surrogate positioning during firing in standing position.

Table 2 — Standing SPL Performance Metric in 2-6 kHz Band (dB Reduction)

Weapon Configuration	Surrogate *left ear* + Helmet (dB)	Surrogate *right ear* + Helmet (dB)	Surrogate *left ear* + Helmet + Armor (dB)	Surrogate *right ear* + Helmet + Armor (dB)
M16 (standing)	-0.1	0.0	+0.2	+0.4
M4 (standing)	+0.2	-0.3	+0.6	-0.8

Additional measurements were made with a human shooter wearing ear clips on both the left and right ears to measure the external ear pressure. The photo in Fig. 16a shows the attachment of the pressure transducer to Jim Faughn's right ear. Figs. 16b-d show ear clip measurements made in the foxhole, standing and prone positions. These measurements were made for a number or reasons including: (1) to assess the direct acoustic path from the muzzle to the left and right external ears and (2) study the application of transfer functions between outer and inner ear using the surrogate laboratory measurements.

Fig. 16 — Photos showing (a) ear clip attachment to ear. Measurements were made with a human wearing the ear clips from (b) foxhole, (c) standing and (d) prone positions.

A few preliminary comments concerning the direct acoustic path and hearing loss in the left vs. right ears of the small weapons shooter are discussed now. The inner and outer ear pressure levels (from the surrogate and from the ear clip measurements) both appear higher on the left ear for the right handed shooter. The left ear is termed the near ear as it faces the primary sound source, the weapon's muzzle. These results would indicate higher hearing loss in the left ear for right handed shooters, and this has been previously found in several studies including the earliest, Prosser S, Tartari MC, Arslan E., Hearing loss in sports hunters exposed to occupational noise, Br J Audio., May;22(2):85-91, 1988. Somewhat anecdotal evidence has been found that contradicts this conclusion with the far right ear suffering more hearing loss for the right handed shooter. In viewing the photo in Fig. 16a, the shooter typically places the right jaw bone tightly against the butt of the weapon to aim and stabilize while firing. One possible explanation is that this could supply a very short bone conduction path with high transmitted levels to the far right ear, thus causing more hearing damage to that ear. Another piece of information obtained from a Research Psychologist at the Visual and Auditory Processes Branch, Army Research Lab is that audiologists have sometimes reported greater hearing loss in the far ear due to the way infantry use hearing protection devices. These subjects revealed that they wear hearing protection in near ear, but not always in the far ear to give them the ability to hear communications with other soldiers and have a better sense of presence.

Transfer functions developed in the laboratory between the outer and inner ear of the surrogate could potentially be used to determine the inner ear pressures from exterior ear pressures measured in the field. If successful, this approach would allow the inner ear pressure to be determined using a human shooter with ear clips in a natural shooting stance. This would greatly simplify field measurements. In this case, the surrogate would not be used at all in the field, allowing increased degrees of freedom to assume standing and prone positions and/or to determine the inner ear pressures when firing other weapons systems.

5. SUMMARY CONCLUSIONS

The surrogate has been validated against human data, and this physical model may serve as a 'standard' for human hearing evaluation of infantry combat equipment deemed relevant to the warfighter. Both laboratory and firing range measurements indicate a SPL reduction of 2-3 dB on both left and right inner ears of the surrogate when a helmet is worn. This reduction is probably due to the helmet blocking the direct acoustic path from weapon muzzle to the ear. Armor appears to have very little effect on the sound reaching the inner ears. The physics of the direct acoustic path from the weapon muzzle to the ears appears to be the most important acoustic mechanism affecting the inner ear SPL levels. The firing range data obtained in this exercise will also be added to a growing database of small arms noise threats that is being compiled at NRL. A complete listing of the shots recorded at the firing range with different weapons and configurations can be found in the table of Appendix II.

Firing range measurements made with both the surrogate and the human shooter wearing ear clips show that the acoustic path is strongest from the weapon muzzle to the near ear (left ear for the right handed shooter) as opposed to the far ear. The logical conclusion would be that hearing loss is worst in the left ear of the right handed shooter. However, there are other possible explanations for greater hearing loss in the far ear that include the short bone conduction path from the weapon through the jaw bone to the far ear as well as the possibility of infantry soldiers neglecting to use ear protection in the far ear to gain a better sense of presence.

This project was partly undertaken when another MCSC PM-ICE project determined that the shock wave from a blast had a complicated interaction with the body armor (increased pressures on neck due to reflections off of the body armor and under the helmet due to wave interference; Mott, D., Schwer, D.,Young T. et al. Blast Induced Pressure Fields Beneath a Military Helmet. 20th International Symposium on Military Aspects of Blast and Shock., Oslo, Norway, September 1-5, 2008. The present project asked the question, "What are the consequences of wearing the body armor on the acoustic signatures in the ear from firing small arms." It was thought that if there were significant spectral features caused by the helmet and body armor, that these differences might be exploited to improve passive hearing protection devices. The results in this report indicate that there are not great differences of the pressures in the ear as a result of wearing the body armor so that a new passive device for this situation will not result from this work.

A quite unique new hearing performance surrogate has been developed that is ready for hearing measurements for future personnel equipment development or for testing the pressures on the ear from any weapons system. Furthermore, it may be possible to discard the surrogate and make such field measurements very simply with a soldier wearing ear clips, once the correlation between the exterior and interior pressure signals is firmly established with the surrogate laboratory measurements.

6. ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of James Faughn, the staff of the M Range and Visual and Auditory Processes Branch, Human Research & Engineering Directorate, Army Research Laboratory, Aberdeen Proving Ground, MD. Much of this work would not have been possible without their skill and dedication.

APPENDIX I: AMPLITUDE AVERAGED CURVES

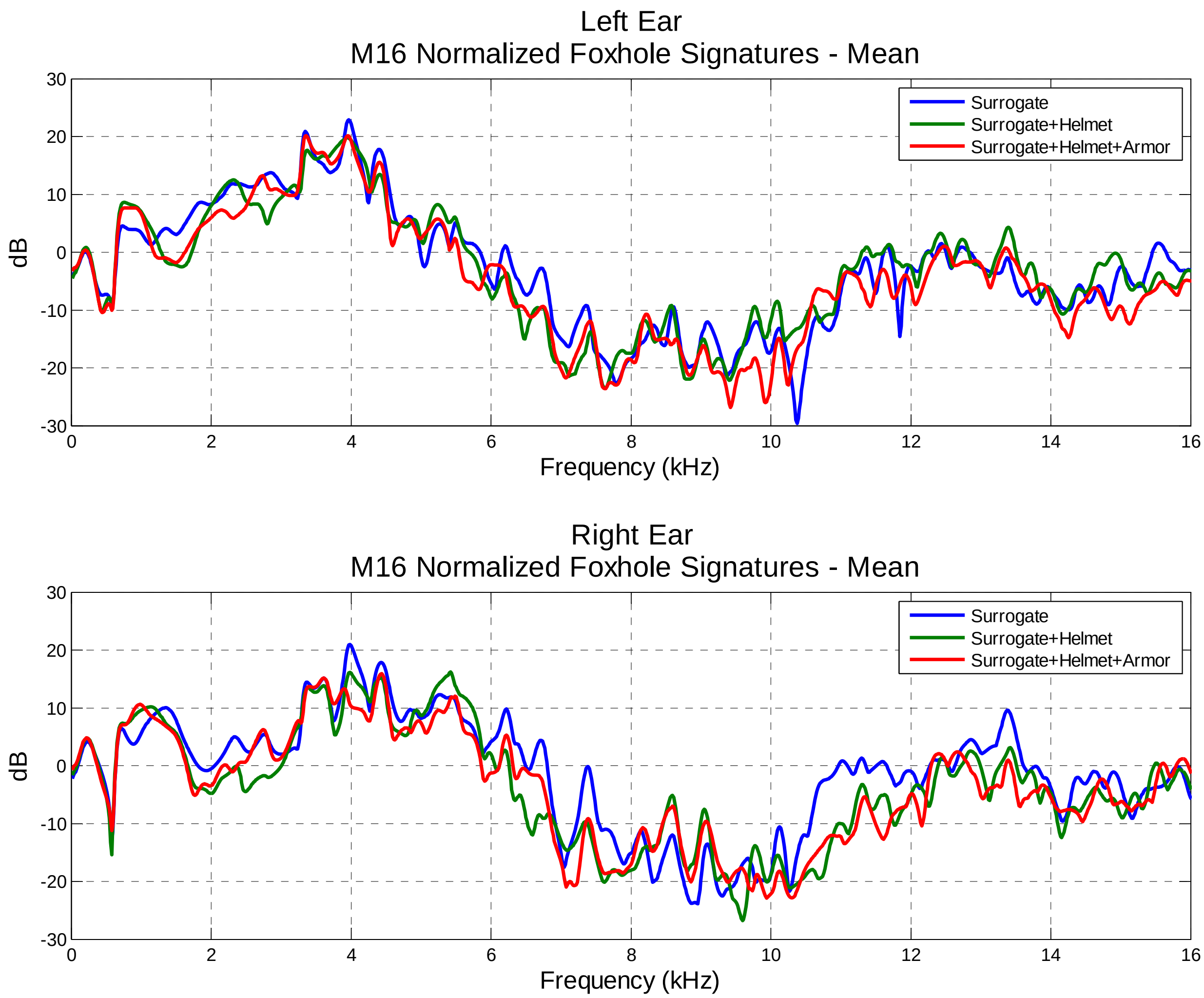


Fig. A1: Displays of amplitude averaged curves for the different equipment configurations using the *M16* weapon fired from the *foxhole*.

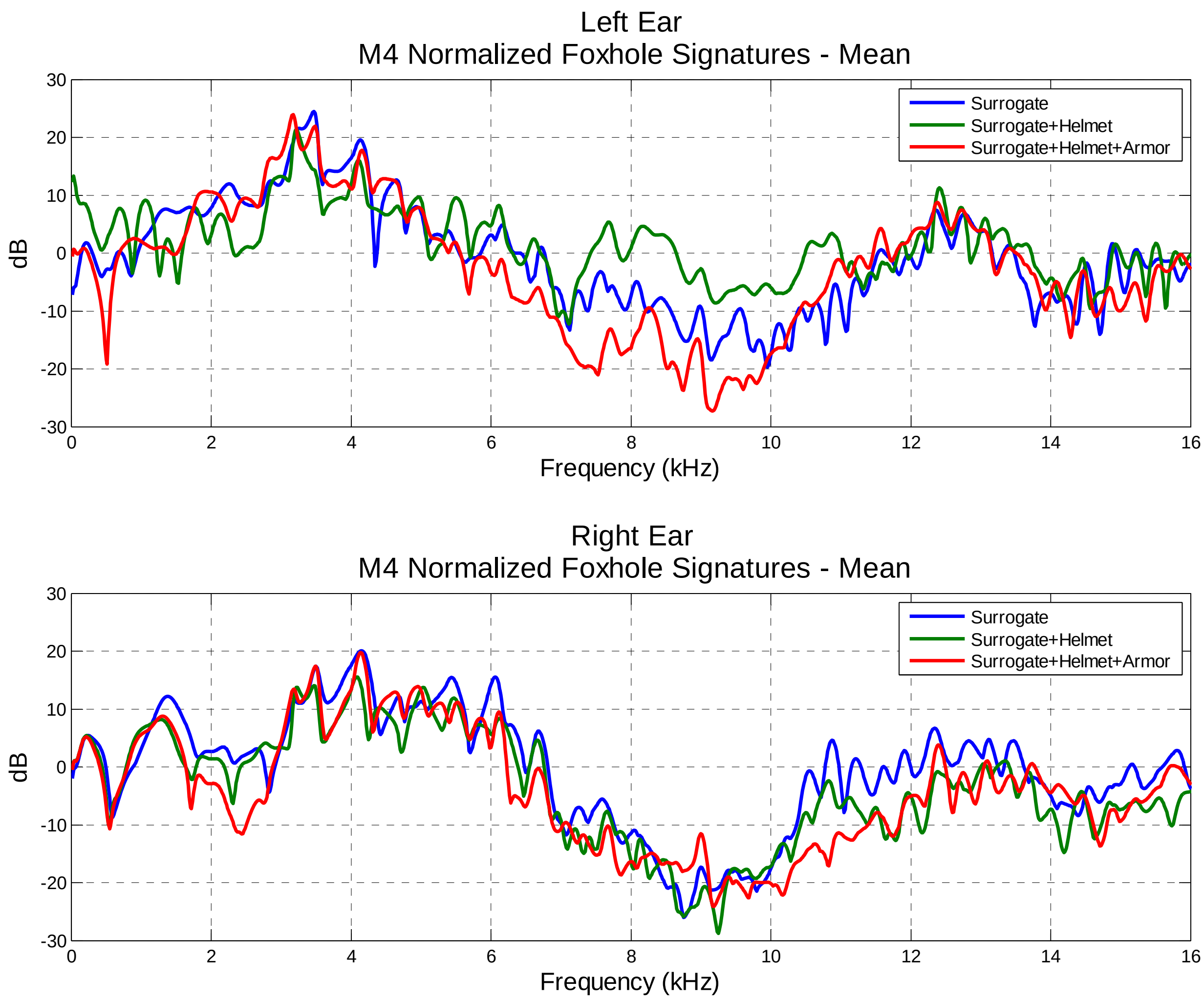
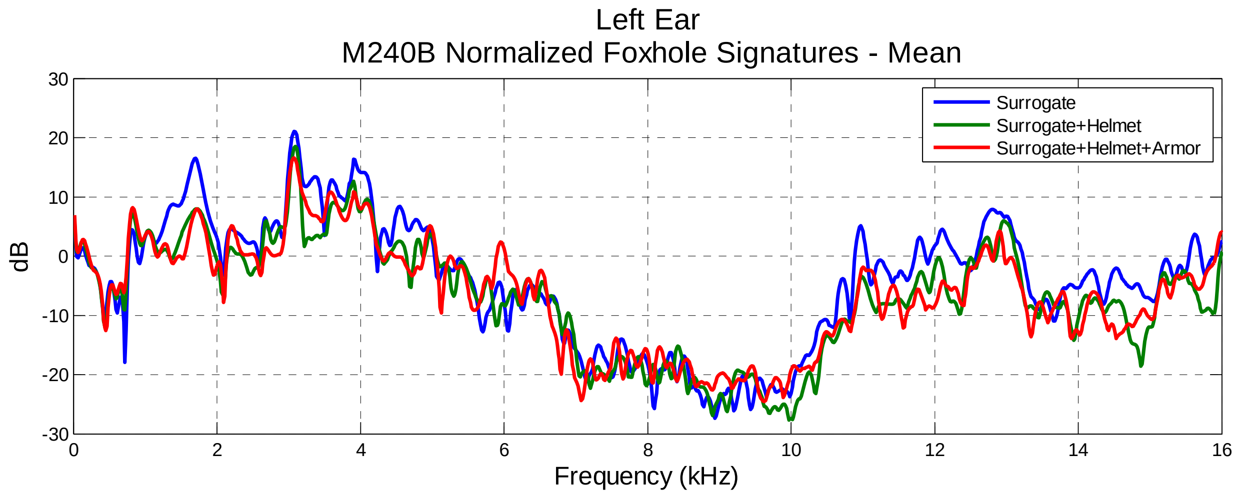


Fig. A2: Displays of amplitude averaged curves for the different equipment configurations using the *M4* weapon fired from the *foxhole*.



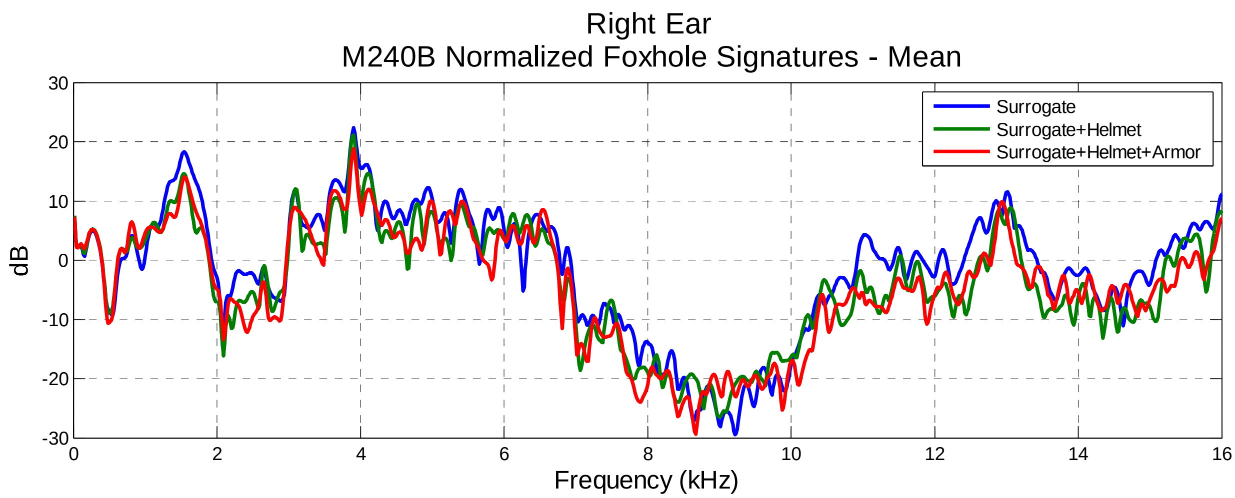
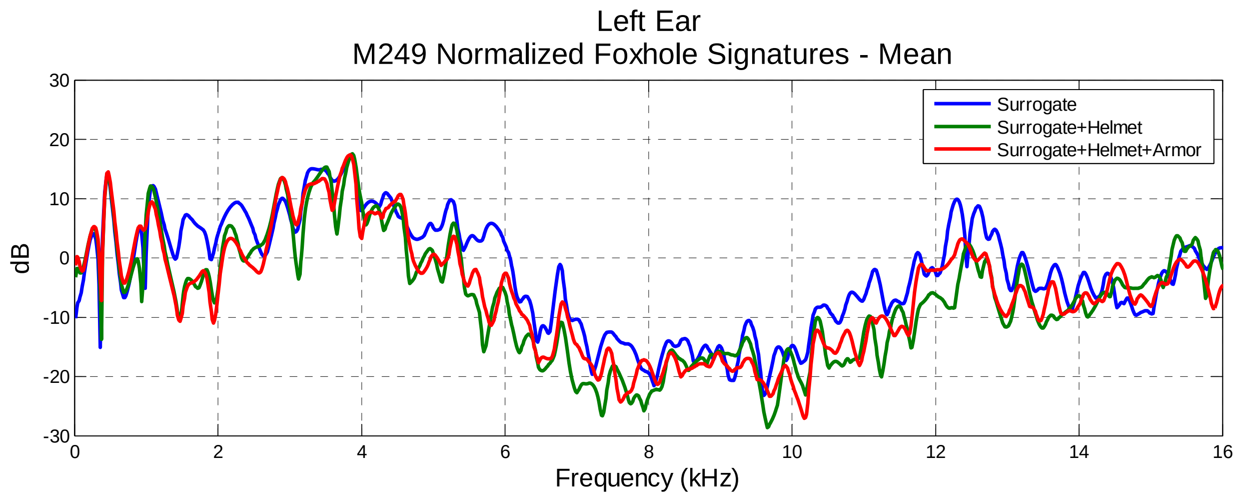


Fig. A3: Displays of amplitude averaged curves for the different equipment configurations using the *M240B* weapon fired from the *foxhole*.



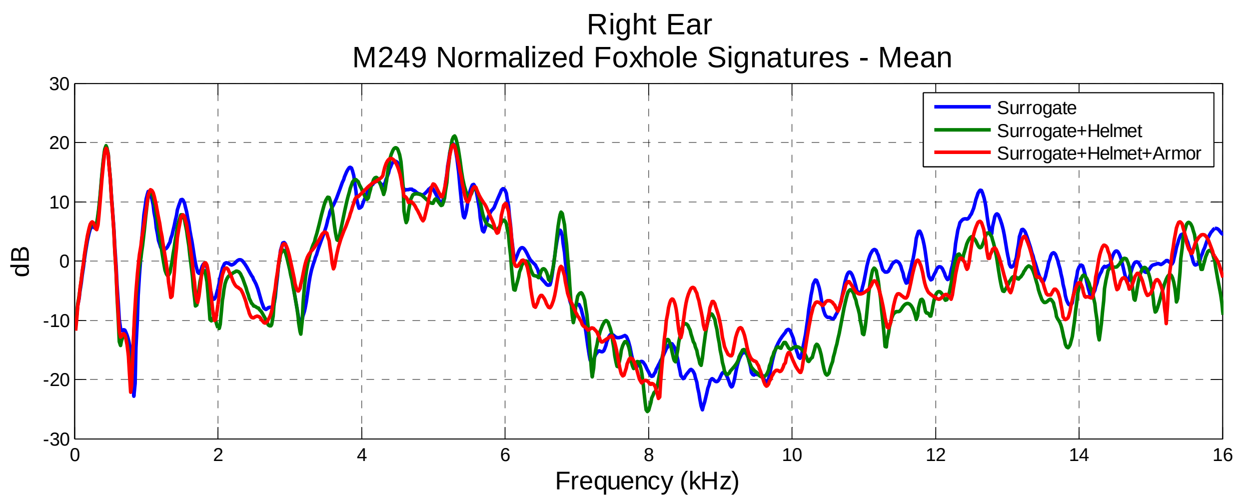


Fig. A4: Displays of amplitude averaged curves for the different equipment configurations using the *M249* weapon fired from the *foxhole*.

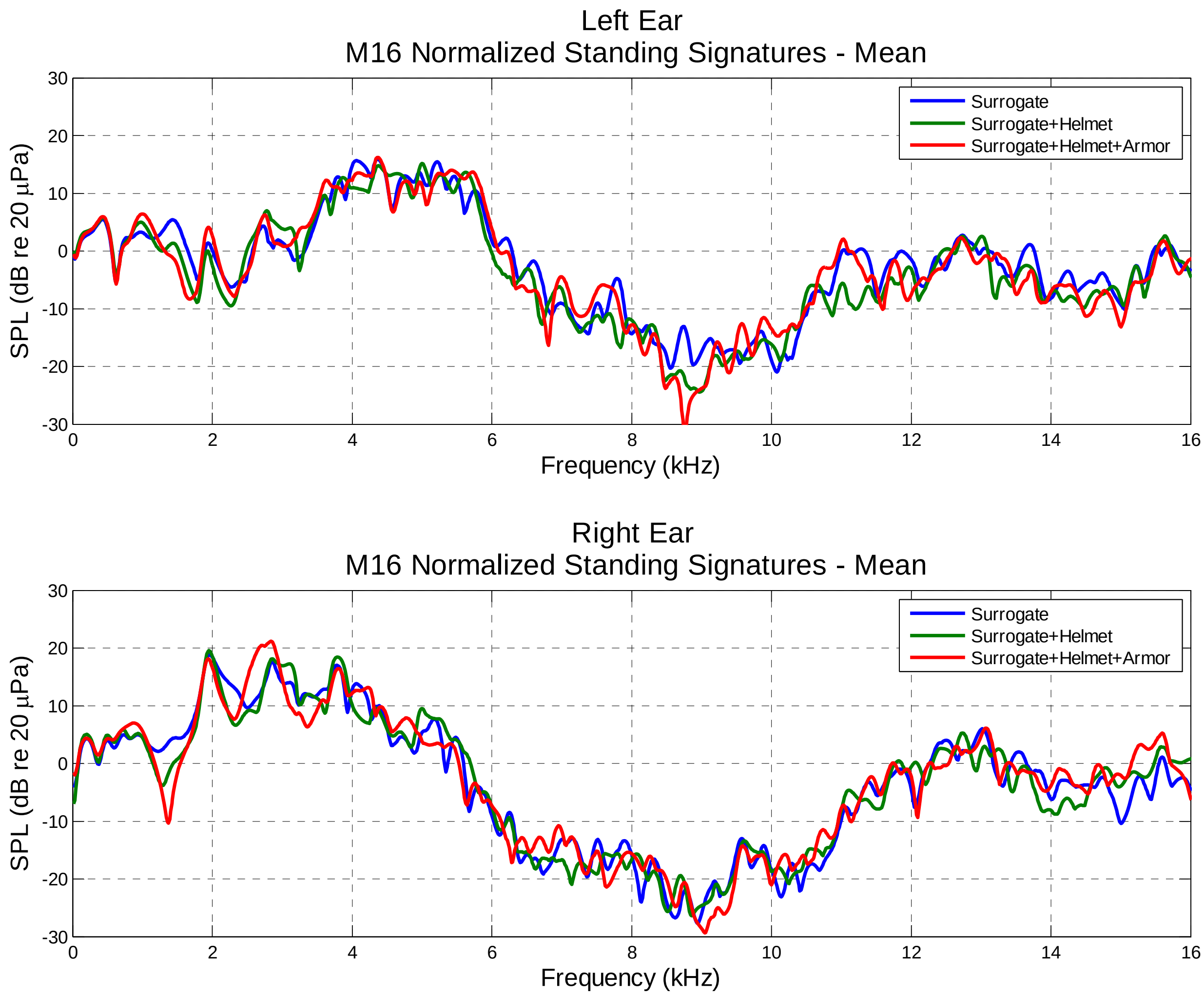


Fig. A5: Displays of amplitude averaged curves for the different equipment configurations using the *M16* weapon fired from the *standing position*.

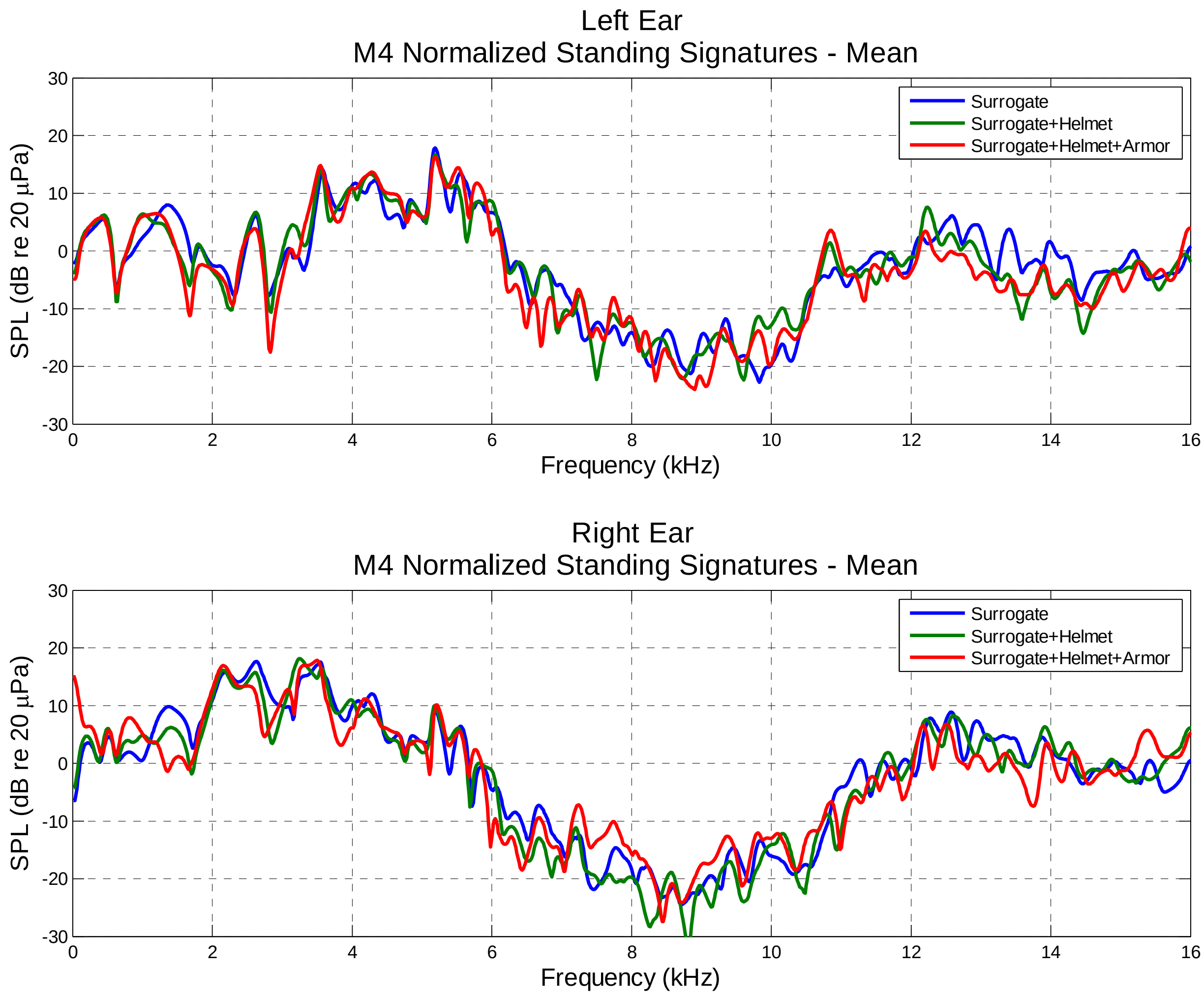


Fig. A6: Displays of amplitude averaged curves for the different equipment configurations using the *M4* weapon fired from the *standing position*.

APPENDIX II: Listing of shots recorded at firing range

Measurement	Equipment Configuration	M4	M16	M240B	M249	M82
Foxhole Reference measurements	Not Applicable	5	5	5		5
Foxhole, Righty shooter, *Surrogate*	None	5	5	5	5	5
Foxhole, Righty shooter, *Surrogate*	Helmet Only	5	5	5	5	5
Foxhole, Righty shooter, *Surrogate*	Helmet and Armor	5	5	5	5	5
Foxhole Reference measurements	Not Applicable	5			5	5
Foxhole, Righty shooter w/ *Ear Clips*	None	5	5	5		5
Foxhole, Righty shooter w/ *Ear Clips*	Helmet Only	5	5	5		
Foxhole, Righty shooter w/ *Ear Clips*	Helmet and Armor	5	5	5		
Foxhole, Lefty shooter w/ *Ear Clips*	None	5	5	5		5
Standing Reference measurements	Not Applicable	5	5			
Standing, Righty shooter, *Surrogate*	None	5	5			
Standing, Righty shooter, *Surrogate*	Helmet Only	5	5			
Standing, Righty shooter, *Surrogate*	Helmet and Armor	5	5			
Standing, Righty shooter w/ *Ear Clips*	None	6	6			
Standing, Righty shooter w/ *Ear Clips*	Helmet Only	6	6			
Standing, Righty shooter w/ *Ear Clips*	Helmet and Armor	6	6			
Prone, Righty shooter w/ *Ear Clips*	None	5	5	5		5
Totals		**88**	**83**	**45**	**20**	**40**